# System design

System overview
LVIS is a pulsed laser altimeter and measures range by timing a short (<10 ns duration) pulse of laser light between the instrument and the target surface. The entire time history of the outgoing and return laser pulses is digitised using a single detector, digitiser and timing clock. This configuration unambiguously describes the range to the surface as well as the vertical distribution of surfaces within each laser footprint.

The LVIS system operates at altitudes up to 10 km AGL and has a 12 degree potential field-of-view (PFOV) within which footprints can be randomly spaced across track. Scanning is performed using galvanometer-driven scan mirrors that control the pointing of both the laser and the telescope instantaneous field-of-view (FOV). Scan mirrors are positioned in a stepped pattern, stopping to fire the laser and integrate the return signal at each beam location. This raster scan pattern efficiently covers 100% of the area within the data swath. Footprint sizes from 1 to 80 m are possible, determined by the AGL altitude of the airplane and the focal length of a diverging lens in the output path. The dual axis transmit scanner allows the swath pattern to remove forward motion of the aircraft from the collection pattern. Roll compensation has also been incorporated into the software for keeping collection directly below the aircraft.

System design
The design goals for LVIS include: wide swath, high-altitude capability, variable sampling pattern and footprint diameter, outgoing and return pulse digitisation, accurate ranging, and automated real-time ground finding/tracking (even in the presence of clouds, atmospheric haze, and significant topographic relief). To achieve the wide data swath using a large aperture telescope and small, high-bandwidth, silicon avalanche photodiode (Si:APD) detectors, the telescope FOV is mechanically scanned across the detector face using a lightweight, galvanometer-driven mirror. Accurate ranging with large footprints requires waveform digitisation of the return pulse to allow compensation for pulse distortion introduced by interaction with complex surfaces. Previous airborne and spaceborne altimeter systems utilised a separate time interval unit (TIU) and waveform digitiser to determine range to the surface and the shape of the return pulse. The TIU timing cannot be related to the waveform more precisely than a single waveform time bin because the TIU and the digitiser utilise separate, asynchronous clocks. The digitiser only scheme employed in LVIS eliminates any ambiguity between the timing and waveform recording functions allowing precise determination of pulse location (<1/10 digitiser bin).

Fig. 2 shows a high-level block diagram of the LVIS sensor design. Table 1 summarises the design parameters of the LVIS system. The system is composed of several sub-systems, all mounted on a 60-cm square, 1.9-cm thick aluminum plate.

Optical system
The receiver system consists of a 200-mm diameter, 5-power telescope with a 25-mm exit pupil. The telescope has a 200-mm aperture, f/2 Petzval1(1 Petzval lens: a high speed, narrow FOV lens composed of two achromatic lenses positioned about an aperture stop; named after the Austrian optician Josef Petzvald) objective with a 400-mm focal length directing light through a 50-mm focal length f/1.8 eyepiece, which produces a 25-mm collimated beam. A scan mirror, located at the exit pupil of the telescope, directs the beam through a 10-nm bandpass filter and onto a 25-mm molded aspheric condenser lens which focuses onto the 0.8-mm Si:APD detector. The scan mirror is a 25x40 mm beryllium mirror that was custom designed to be lightweight for fast scanning, yet stiff enough to remain flat during and just after the intense acceleration of scanning. The receiver box can accommodate two more detectors, enabling the simultaneous collection of dual-wavelength, dual-polarisation data.

Table 1: System characteristics of the LVIS altimeter

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|---|---|
| Telescope aperture | 20 |
| Telescope total FOV | 200 mrad |
| Detector FOV | 8 mrad |
| Detector band width | 90 MHz |
| Bandpass filter band width | 10 nm |
| Digitiser sampling rate | 500 Msamp/s |
| Digitiser effective bits | 7 |
| Laser output energy | 5 mJ |
| Laser pulse width | 10 ns (FWHM*) |
| Laser spatial energy pattern | TEM00 single mode |
| Pulse repetition rate rep-rate | 100 to 500 Hz |
| Laser output wavelength | 1064 nm |
| Data rate at 500 Hz rep-rate | 300 kbytes/s |
| Swath width at 10 km altitude | 2.0 km |
| Footprint diameter | 1 to 80 m |
| Maximum operating altitude | >10 km |

*Full width at half maximum.

Laser
The transmitter is a water-cooled, solid-state, diode-pumped, Nd:YAG oscillator-only laser, designed and manufactured by Cutting Edge Optronics
(St. Louis, MO). The laser cavity is housed in a hermetically sealed aluminum enclosure that measures 45x13x13 cm. Operating at rates of up to 500 Hz, the laser emits 5 mJ, 10 ns, Gaussian-shaped (temporally and spatially) optical pulses at a wavelength of 1064 nm. Accurate ranging to a mean elevation in a wide laser footprint can be confounded by a complex spatial energy distribution across the laser spot, thus, the laser transmitter was required to have a single-spatial mode (TEM00) energy pattern. A fiber-coupling lens is placed behind the final

turning mirror inside the laser enclosure to capture a small amount (<1%) of the laser output and direct it through two optical fibers (start pulse and calibration pulse with 100 m (300 ns) delay). The laser output beam is directed through the output scanner box containing filter wheels to control the output power to optimise return signal strength, a diverging lens to control the size of the footprint on the surface, a lockable pitch control for boresighting, and the galvanometer-driven output scan mirror.

Altimetry and waveform analysis electronics

The digitiser-only altimetry electronics scheme is a unique feature of the LVIS instrument; all of the

pulse discrimination, ranging, range gating, and transmit and receive pulse shape recording are performed using a single detector, digitiser (Signatec, Corona, CA), and oscillator (HP model 8657B disciplined by a 10 MHz rubidium oscillator reference signal). The entire time history of the detector output is recorded at 500 Msamp/s with 8 bit resolution from before the laser is fired until beyond any possible surface returns. Noise statistics (mean and standard deviation) for generating pulse finding criteria are calculated for each shot from a section of time/memory that is beyond any possible surface return, thus ensuring that it is signal-free. The digitiser, triggered by the laser Q-switch pulse, begins digitising slightly before the output pulse and continues for 120 ms (~20 km in range). A real-time ground finding algorithm searches a 2-km window that is automatically centred on a valid ground location from a previous shot. The search routine returns the location of the first signal detected searching from the back of the window; thus, ground returns are found before cloud returns eliminating the need for range gating.

Fig. 3. The LVIS real-time ground finding algorithm. Central figure shows an amplitude vs. range plot of the detector output. The 2-km window in the digitiser record is searched from the back to locate the surface return. (a) Window return, start pulse, and fiber calibration pulse. (b) Returns from an optically opaque cloud layer between the aircraft and the ground. (c) Vegetated surface return. Left-most signal is from vegetation, right-most pulse is the sub-canopy ground return. (d) Digitised noise used to calculate noise statistics for the search algorithm.

Real-time data system

The real-time data system consists of an Intel Pentium 4 based linux system. The interrupt-driven, real-time control software was written using FSM Labs
Real Time Linux extensions. The real-time module attaches to the standard linux kernel, allowing the acquisition software direct and preemptive access to system hardware while full linux functionality is preserved. User space software communicates with the real-time acquisition software via memory buffer devices, enabling all non-critical calculations and data display to happen without interfering with data collection. Data is written into binary files onto a removeable hard disk for easy post mission downloading and the data is also copied to an external drive or laptop via the network after a flight.

All sub-systems are hardware triggered via a TTL fanout device triggering from the laser Q-switch trigger coming from the laser controller unit. This pulse triggers the digitiser, a gps disciplined timing card and the real-time kernel module simultaneously. Time stamping of the laser pulse is achieved with a Symmetricom (formerly TrueTime) GPS-PCI card. Our attitude and position is provided by an Applanix POS-A/V system with the gyro mounted directly on sensor head, very near the dual axis transmit scanners.

The Applanix system yields a very accurate position and angle orientation for the plane at 200 Hz which is tied to GPS time. A physical survey of the plane for each installation yields the physical offsets between the instrument, the gyro location and the GPS antenna. Fusion of the Applanix position and orientation data and the LVIS ranging data is straight forward with both systems using GPS time as their basis.